Model Review and Clarification for:
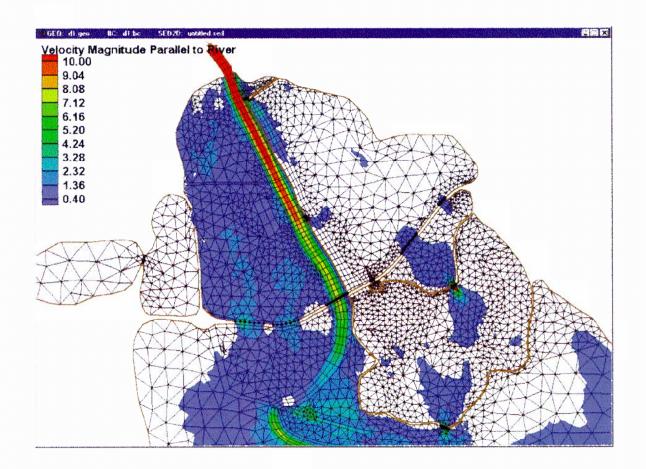
Hydraulic Models of the Congaree River in Richland and Lexington Counties, SC

Introduction for SMS, ███████ and ██████████

███████████ asked me to prepare a statement of introduction to provide a little background on myself, the Surface-water Modeling System (SMS) and ███████████ who will be presenting a clarification of the differences he and I determined as we reviewed the RMA2 numerical models generated by FEMA in their study from 2000 and by Exponent Inc in 2001.

Biography of ███████████

███████████ graduated with a Masters of Science degree in 1989 and a Ph.D. in Civil and Environmental Engineering in 1994 from Brigham Young University (BYU). His graduate research was based on numerical and geometrical modeling on the computer with an emphasis on computer graphics to visualize engineering processes. As a student, in 1986, he began working with a research group at BYU then known as the Engineering Computer Graphics Laboratory (ECGL), which developed general purpose computer graphics software packages that have been used in academia, government, and commercial applications since the early 1970s. While working on his doctrate degree, he supervised the development of these programs. Since 1991 he has applied his computer modeling and graphics experience to the modeling and visualization of hydraulics. The ECGL was reorganized into what is now known as the Environmental Modeling Research Laboratory (EMRL), and maintains three programs for groundwater, watershed, and surface water modeling. ███████████ has overseen the development of SMS since 1991. In addition to developing SMS, ███████████ has been involved in training professional engineers to use the models interfaced through SMS. He has taught short courses for NHI, ASCE, USACE, and commercial engineering corporations such as Michael Baker (a technical contractor for FEMA) for the past six years. He has applied the models RMA2 and Flo2DH in several consulting applications and reviewed numerous studies over the course of that time.

History of SMS

The data required for a complex hydrodynamic analysis can be overwhelming. The detailed and meticulous tasks of gathering, organizing and manipulating this data by hand results in human error and less acurate representation of the domain. Such hand built studies are greatly simplified models which produce simplified results. SMS is a product of over 12 years of development to automate the creation, management, and visualization of this data. This set of tools allows the engineer to concentrate on how the situation should be modeled and then model it accordingly.

SMS was developed from earlier programs to perform the same tasks. The earliest, called NGRID was funded by the United States Army Corp of Engineers, Waterways Experiment Station (USACE-WES) and developed at the Univeristy of Texas in Austin by ███████████ while he was a graduate student in 1989-1990. ██████ was

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hired by the BYU Civil and Environment Engineering Department in January of 1991. He became part of the ECGL and his tools were integrated into the computer graphics programs generated at BYU to create a program called FastTABS. In 1993, due to the fact that more computer models were being incorporated into the system, FastTABS was redesigned and implemented as the Surface-water Modeling System (SMS). Currently, SMS is partially sponsored by the USACE-WES and the FHWA. It is used by these governmental agencies as well as by several other agencies including the USGS, Bureau of Reclamation and others. The program is distributed commercially by Environment Modeling Systems Inc., which provides software, training and consulting services in the environmental engineering fields.

The use of two-dimensional hydraulic models is still a relatively new field, and as such does not have the exposure nor wide spread application that a model such as HEC-2 has had. However, it has been refined in applications for the past 15 years, and its necessity is becoming globally recognized while its use is expanding. Currently there are registered SMS users in over 40 countries worldwide. The number of engineers experienced and qualified to use these models is not huge, but is also expanding with additional applications and training courses from various sponsors.

Biography of ███████████

Due to the fact that ████████ had a previously scheduled trip to Hawaii with his wife, he is unable to attend this meeting. Therefore, he will be represented by ██████ ████████. Mr. ████████ started working for the EMRL as a part-time undergraduate student in 1995. He graduated in April, 1996 and soon afterward started working as a full time Research Associate and SMS Software Manager. He graduated with a Masters degree in Civil and Environmental Engineering in April, 2000.

████████ has extensive experience with the RMA2 model, both in development of the interface and in applying the model to real-world applications. He has been an instructor in various SMS training courses since 1996, and has given on-site training to parties that use the SMS software. In addition, he has helped to develop finite element models for various consulting firms around the US and firms in Canada, Puerto Rico, and Korea.

Summary

Darren will be presenting the results of a clarification of the RMA2 models used to evaluate and present the hydraulic conditions in Richland and Lexington Counties, South Carolina. While we were asked by ████████ to provide this clarification, I would like to stress that these comments and suggestions would not change if FEMA had asked for our input. Our clarification, which ████ will present is that the Exponent study gives a superior representation of the complex flow conditions behind the Manning Levee and should be used in determination of floodway ahead of the FEMA study. Further, both two-dimensional studies show that HEC-2 is inappropriate for this determination.

Model Review and Clarification for:

Hydraulic Models of the Congaree River in Richland and Lexington Counties, SC

Tuesday, April 24, 2001

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Model Review and Clarification for:

Hydraulic Models of the Congaree River in Richland and Lexington Counties, SC

Executive Summary

The existence of the Manning Levee affects the flow attributes in Richland County, South Carolina to the extent that one-dimensional flow assumptions do not apply in the region. Both FEMA and Exponent have provided RMA2 analyses that clearly show two-dimensional attributes around the levee during the 100-year flood event. FEMA utilized a coarse mesh originally created by hand in 1981. Exponent has generated a superior mesh that represents the geometry of the region with increased detail and appropriately covers a more extensive area. Because one-dimensional models such as HEC-2 rely on one-dimensional flow assumptions to determine floodways, their application in this situation are inappropriate. Various scenarios have been evaluated by Exponent to consider possible flooding cases. These are included in the Exponent report. These results are reproducible based on the underlying roughness data, geometry and material zones. Our review has concluded that the Exponent model is more suited to be the basis for future consideration of other possible flood conditions if required.

Page 7-4 of the FEMA Study Contractor Guidelines states:

The floodway widths will be computed for the "without levee" condition if the levees do not meet the requirements of 44 CFR 65.10. The equal conveyance reduction method should be considered, if it is technically appropriate.

The Manning Levee does not meet the specified requirements. However, based on the complex nature of the flow behind the Manning Levee, and the historical impact the existence of the levee has had, two-dimensional analysis should be used in the determination of no floodway on the Richland County side of Manning Levee.

Introduction

Two-dimensional hydraulic models of the Congaree River in Richland and Lexington counties have been used to evaluate flow patterns and potential floodways. Two studies were evaluated in a comparison performed by ███████████ (Assistant Professor in the Department Civil and Environmental Engineering at Brigham Young University) and ███████████ (Research Associate). The two studies were originally performed by FEMA and Exponent, Inc.

The FEMA study was based on finite element meshes originally constructed in 1981 by the USGS. For the study, two meshes where merged into one. The merged mesh is shown in Figure 1. The study is described in a report entitled "Appeal Resolution for Congaree River in Richland and Lexington Counties, South Carolina" dated September 26, 2000.
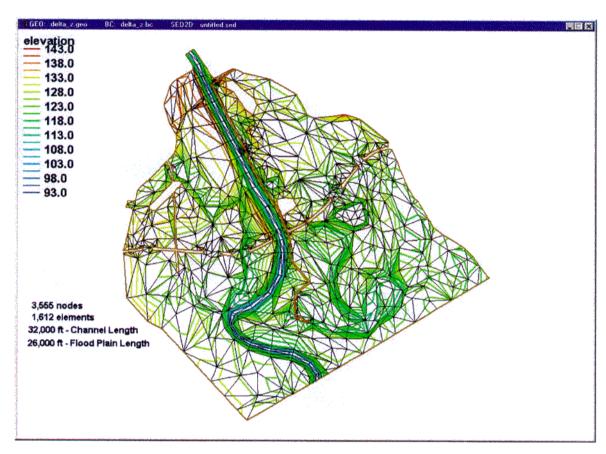
Figure 1: Mesh used in FEMA study

An expanded and refined finite element mesh was constructed for the Exponent study. This mesh is shown in Figure 2. The Exponent study is described in a report entitled "Expanded Two Dimensional Flow Analysis and Determination of No Floodway for the Congaree River Floodplain in Richland County, South Carolina", dated February 12, 2001.
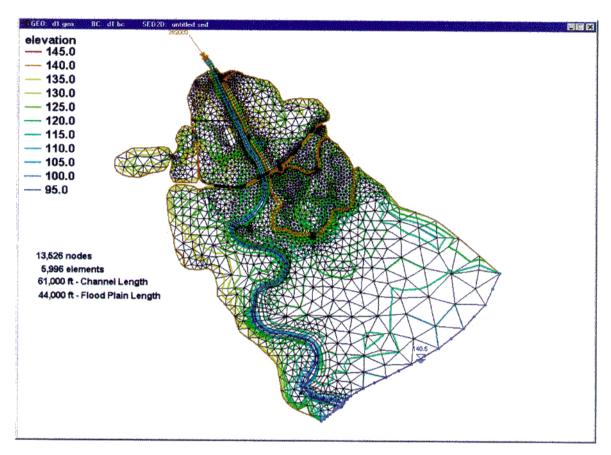
Figure 2: Mesh used in Exponent study

The purpose of this evaluation was to determine what improvements and clarifications were made by both studies in understanding the hydraulic attributes of the floodplain in Richland County along with how those clarifications were applied to generate the floodway definition in the area of the studies.

Study Description and Objectives

Both studies used the United States Army Corp of Engineers analysis code RMA2 to focus on the area east of the Congaree River in Richland County, which lies behind the Manning Levee. The objective is to understand the flow in this region in order to define a FEMA flood insurance rate map (FIRM).

The Manning Levee has been in place along the east bank for a very long time and has influenced the hydraulic conductivity as well as the management and development of the floodplain. Up until 1998, all FIRMs recognized this levee in their definition of floodways and no floodway was defined on the Richland side of the levee. Over the past few years, various FIRMs have been proposed but not yet accepted as a result of ongoing studies, including the FEMA study evaluated as part of this work. Based on the FEMA study reviewed here, a proposed FIRM was generated which included a floodway behind the Manning Levee. This conclusion was reached using the following logic and process:

- Two-dimensional analysis shows that approximately 9% of the flood waters in the 100-year flood event would be conveyed through Richland County, behind Manning Levee.

- Flow behind the levee is not aligned to the river, nor is it consistent, therefore a 1.0 ft/sec threshold was used to determine areas of effective flow.

- One-dimensional cross sections were defined to determine a floodway location, ignoring Manning Levee due to the fact that conveyance occurs behind the levee. Two-dimensional results were then ignored, except for use to limit the cross sections to the areas previously defined as effective flow.

Points of Comparison

The two studies were compared in several areas. First was a review of the underlying bathymetry and topography data, as well as the definition of material zones. Second, the mesh quality for each mesh was reviewed. The applied model parameters were then compared. Finally, the results generated by the two models were evaluated.

Underlying Data: No numerical model is better than the data used to construct the model. The geometry of a finite element mesh has by far the greatest impact of the accuracy of a numerical model. In the FEMA study, the principal source of bathymetric data was from the 1981 USGS study. FEMA indicated that they had compared these data with updated contour maps to check elevations, and this resulted in higher elevations in some of the areas behind Manning Levee. The Exponent study used entirely new geometric data obtained from recent surveys. Comparison of the geometry (Figure 3) show that in the principal areas the ground elevation used are very similar. The blue areas below the I-77 embankments illustrate the difference in representation of the Gill Creek Levee. The FEMA study has higher ground elevations, whereas the Exponent study modeled the levee as a flow restricting feature (similar to the I-77 embankment). The biggest difference is the extent of the data. Figure 3 shows the extent of the FEMA study, because that is where a comparison can be made. However the Exponent study extends 16,000 ft further down the floodplain.

Both studies utilized recent aerial photos to reclassify the material zones. Both also used the same roughness values for those zones. However, due to a higher resolution in the finite element mesh, the definition of the material zones is superior in the Exponent study.
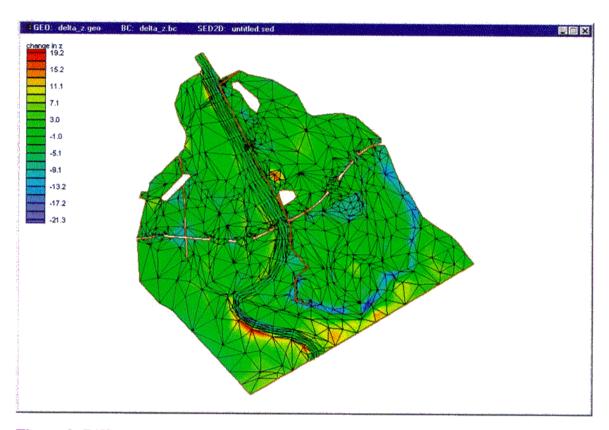
Figure 3: Difference in ground elevations.

Mesh Quality: Mesh quality includes analysis of element quality, element density and resolution, and domain extents. The shape, quality, and number of elements in an RMA2 model have an affect on its stability and validity of the model results. Skewed triangular elements in particular with interior angles less than about 10° can produce erroneous results. SMS includes an option to display warnings about mesh elements that violate these rules. Figure 4 shows the warnings that were generated for the standard recommendations in SMS for the two meshes. In these pictures, any color indicates a possible concern. These figures indicate a superior quality of the Exponent mesh.
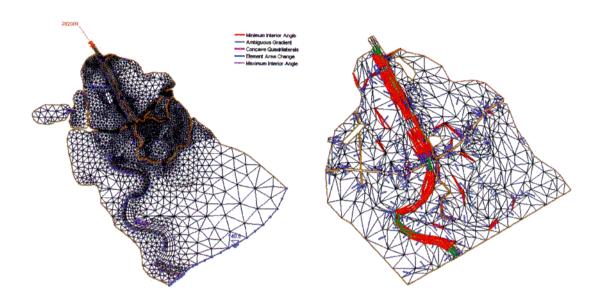
Figure 4: Mesh quality warnings

A higher resolution of elements increases the computation time required but can produce more a accurate solution due to more points of computation. The 2000 FEMA study used a finite element mesh that was originally prepared by the USGS in 1982. At the time of the original study, lack of efficient interface tools, time and cost limitations did not allow for a more developed mesh. Although the SMS technology was available in 2000, it was apparently not used to its full potential because the original rough mesh from 1982 was utilized in the FEMA study with only modifications of updated bathymetry. The Exponent study took advantage of the SMS tools and developed a new finite element model. There was much better mesh refinement in the Exponent study than in the FEMA study, leading to a higher resolution in the solution.

Model Parameters: Generally speaking, the Exponent study was carried out to match the FEMA study as much as possible in the area of model parameters. For example, Manning's roughness values from the FEMA studied were applied in the Exponent study. This was apparently done to minimize the variables when the studies are compared. However, in some situations, changes were justified. A certain measured down stream high water mark was used as a boundary condition specified at the outflow boundary in each study. A USGS review of the FEMA study commented that the downstream boundary condition was incorrectly specified because the high water mark was observed further downstream than the FEMA mesh extended. Previous applications of that mesh had used one-dimensional analysis to compute a boundary condition at the lower end of the mesh. The Exponent study extended the mesh, resulting in the boundary condition being appropriately applied without further adjustment compared to FEMA. A second vital consideration for extending the mesh is that boundary conditions control the

performance of the model in their immediate area. They should be kept away from the area of concern, and close to locations where valid data can be obtained. Extending the mesh allows the model to do its job in the area of concern.

Summary of FEMA Study

The FEMA study was based on previous studies that have been effectively used in the past for design and management of this area. The study gives a good idea of the two-dimensional nature of flow behind and below Manning Levee. However, these results were then ignored and a one-dimensional model with one-dimensional assumptions were used to determine the resulting floodway.

The FEMA study made use of an existing mesh in order to be efficient. This resulted in the model being limited to the resolution and extents of the older mesh. As has been mentioned, the downstream boundary condition was lower than was justified. A lower water surface would naturally result in higher velocities. The FEMA study used these higher velocities to delineate effective flow regions for the one-dimensional model. A larger effective flow region in the one-dimensional model results in a larger floodway. Therefore, the final conclusions of the FEMA study were significantly affected by the limitations of the old mesh.

Additionally, velocities reported by the FEMA study were further increased by the application of the maximum historical flood as opposed to the 1% flood. This further increased the assumed effective flow regions in the HEC-2 model.

Summary of Exponent Study

The Exponent study resolved several of the problems which have been pointed out in the FEMA study. An improved mesh was generated to clarify the flow conditions. The extension to the model domain clarified how the downstream boundary condition should be specified. A more accurate representation of the geometry and material zones in the floodplain resulted in a clarification of flow conditions in general.

Several minor refinements to the Exponent mesh were suggested during the course of this review. These included some poorly formed elements, and numerical convergence concerns. Each problem was easily resolved and had no significant impact on the model results.

2D –vs- 1D Hydraulic Modeling

The purpose of both studies was to better understand the flow conditions that would exist during a 1% flood event on the Congaree River. This information would be used to determine the floodway through Richland and Lexington Counties. Both studies effectively showed that the flow around the Manning Levee and through the relief openings in the I-77 embankment have strong two-dimensional characteristics. However, the FEMA report (pg 24) states:

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"The two-dimensional flow model (RMA2) was used as a decision-making tool, however, the BFEs shown on the FIRMS are based on a one-dimensional flow model (HEC-2). This was done because HEC-2 is the most common hydraulic program used in FISs nationwide. HEC-2 is available free of charge, and a large number of engineers are familiar with it, facilitating future revisions. While RMA2 provides more detail about flow on a wide floodplain, HEC-2 can be calibrated to closely match these results. Most significantly, HEC-2 has established, equitable methods for determining a floodway, while RMA2 has no floodway determination tools."

The following paragraphs discuss our thoughts on each of these given reasons for using the one-dimensional HEC-2 model over the two-dimensional RMA2 model.

"HEC-2 is the most common": Simply because a tool is common, does not make it the right tool for the job. Such an attitude would eliminate the advent of new technology. Both RMA2 studies clearly showed the inadequacies of one-dimensional assumptions in this case. Therefore, the tool does not fit.

"HEC-2 is available free of charge": RMA2 is also free of charge. The graphical interface (SMS) used to efficiently build and visualize the results of RMA2 is sold commercially. However, even this cost is not a prohibitive reason for not utilizing the technology.

"A large number of engineers are familiar with HEC-2": This is true, but many engineers are also familiar with RMA2, and the number continues to grow. Besides this, the tool still does not fit the job. If your car's transmission broke, you wouldn't take it to a locksmith just because there are more of them around.

"HEC-2 can be calibrated to closely match these results of RMA2": This is only true if one-dimensional flow exists in the region being represented. The flow is not one-dimensional on the floodplain of the Congaree River. While HEC-2 can produce answers that match at certain points of the 2D mesh, one HEC-2 location represents a wide range of solutions across an entire section of the RMA2 mesh. A single point cannot be fully calibrated to a range of values.

"HEC-2 has established, equitable methods for determining a floodway, while RMA2 has no floodway determination tools": It is true that the RMA2 model has not established automated methods for determining the floodway. However, a floodway can be determined using the capabilities inside SMS. Furthermore, the tools included in HEC-2 rely on the 1D assumptions of HEC-2. If those assumptions were not valid, the floodway computed by those tools would be equally invalid.

Floodway Determination

The definition of a floodway generally includes the area adjacent to a river that is required to convey the flood waters in an efficient manner. In FEMA's study, it is obvious that the technical definition does not apply to all cases. The study tries to ignore the Manning Levee because it is not a certified 100 year levee, but the existence of the

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two-dimensional study itself shows that FEMA agrees the levee changes the flow attributes in the region. The key point that must be examined to define the floodway in this region is the determination of areas of effective or efficient flow. An addition factor is the consideration of historical features such as the Manning Levee.

Efficient Flow

When determining if the flow in the Richland County floodplain is a floodway, the flow conditions need to be examined. If there is no efficient flow, there cannot be floodway. The FEMA study established a 1 ft/sec velocity magnitude for effective flow. However, behind the Manning Levee, the flow direction is not parallel to the river. The velocity magnitude parallel to the river can be computed using the tools inside SMS. For the 1% flow rate, for what Exponent called CASE 3 (two breaches of Manning Levee), the areas where water is moving parallel to the river faster than 0.4 ft/sec are shown in Figure 5. This figure shows that water does not flow in an efficient manner that would be expected in the floodway. This clarifies the condition of flow behind the levee.
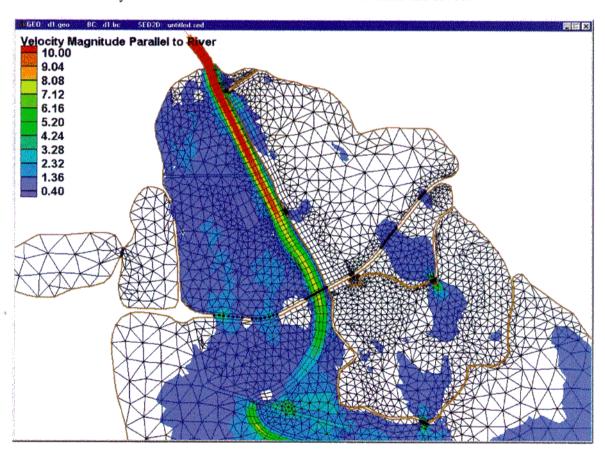
Figure 5: Velocity magnitude parallel to the river.

Historical Factors
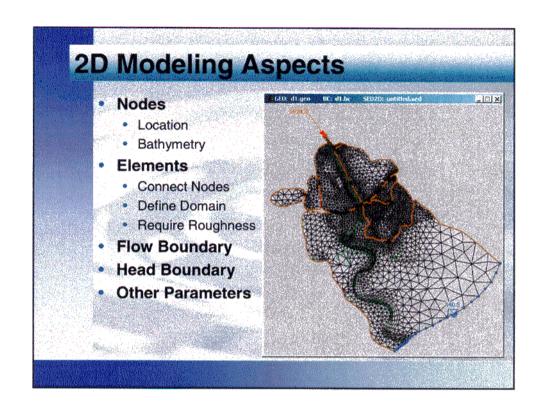
By strict definition, Manning Levee is not a 100 year levee, and therefore could be ignored when computing a floodway for the Congaree River. However, it has not been ignored in other hydraulic design considerations over the past several decades. The I-77 relief openings were obviously designed without a floodway in mind. This is evidenced by the fact that the large 1300-foot relief opening is not positioned near the river (which probably would create an efficient floodway), but rather in the middle of the floodplain. While it is true that a Manning Levee breach is expected during the 1% event, and that such a breach will allow up to 9% of the flood waters to pass through Richland County, it is also true that the levee significantly modifies the hydraulic nature of the floodplain. It does this by its own existence as well as through the influence it has had on other levees and embankments that have been added to the floodplain since it was built.

Model Review and Clarification for:
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Richland and Lexington Counties, SC

by

Outline

- **2D Modeling**
- **The Need For a Tool**
- **SMS**
  - History
  - Mesh Construction
  - Visualization
- **Flow Conditions in Congaree River Floodplain**
- **Comparison of the Two Studies**

2D Modeling Aspects

- **Nodes**
  - Location
  - Bathymetry
- **Elements**
  - Connect Nodes
  - Define Domain
  - Require Roughness
- **Flow Boundary**
- **Head Boundary**
- **Other Parameters**

The Need For a Tool!

- **2D Modeling Prior to SMS**
  - Extremely Time Consuming
  - Extremely Expensive
  - Difficult to Analyze Results
  - Not Often Utilized
- **With a Tool Like SMS**
  - Drastic Increase in Productivity
  - Visualization Assist Model Analysis
  - 2D Models Can be Utilized

History of SMS

Under development since 1990

Distributed free to government sponsors (600+ users)

- USACE-WES

- FHWA and State DOTs

Distributed for commercial use through Environmental Modeling Systems Inc. (EMS-I)
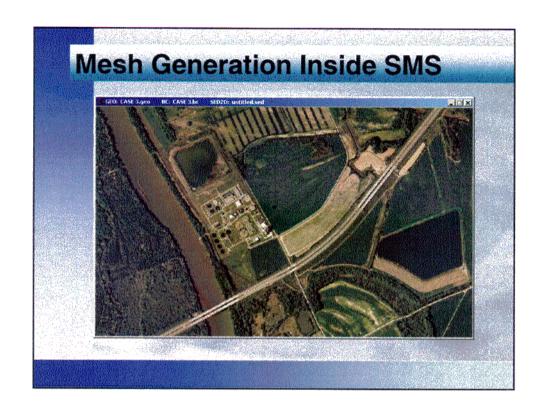
900+ private licenses
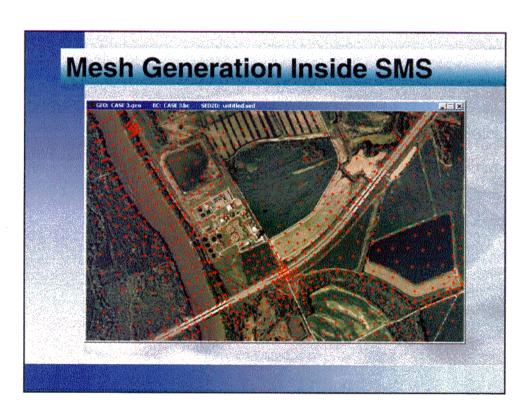
Both Gov. & private use rapidly expanding
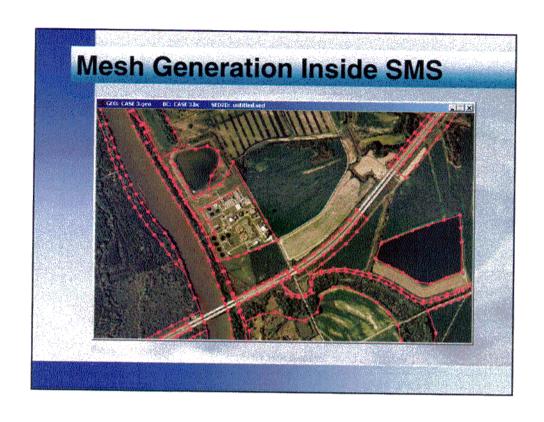
2D Mesh Definition

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GNN	3		2002403.6200			735106.0000					113.0000
GNN	5		2003134.2500			735686.7500					110.0000
GNN	7		2003490.1200			735949.0000					105.0000
GNN	9		2003916.3800			736213.5600					100.0000
GNN	11		2004105.8800			736384.1200					96.8000
GNN	13		2004254.0000			736550.6200					96.8000
GNN	15		2004371.8800			736735.1200					100.0000
GNN	17		2005197.6200			737568.3100					110.0000
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GCL    4    8484    8649    8462   -1
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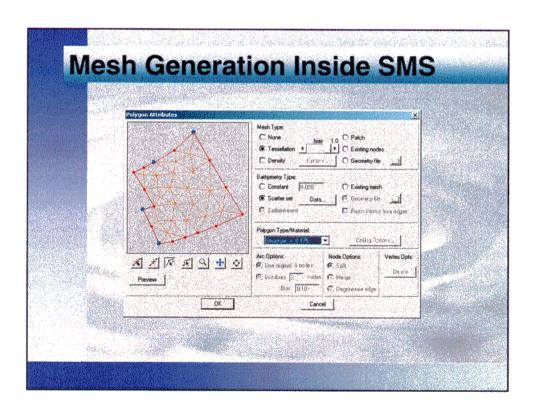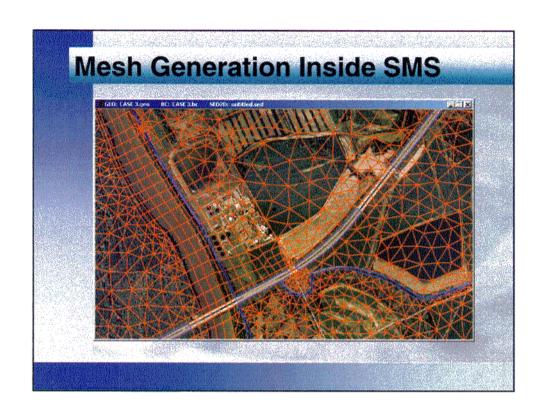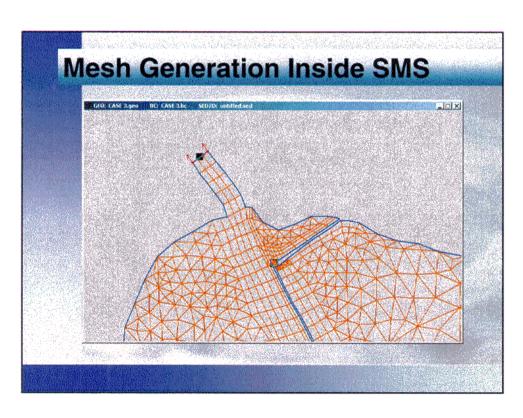
Mesh Generation Inside SMS

Mesh Generation Inside SMS

Mesh Generation Inside SMS

Mesh Generation Inside SMS

Mesh Generation Inside SMS

Mesh Generation Inside SMS

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Mesh Generation Inside SMS
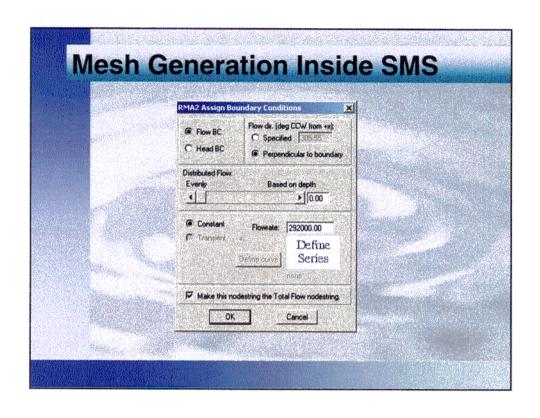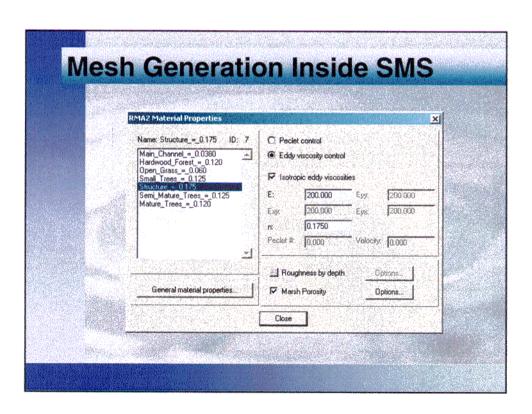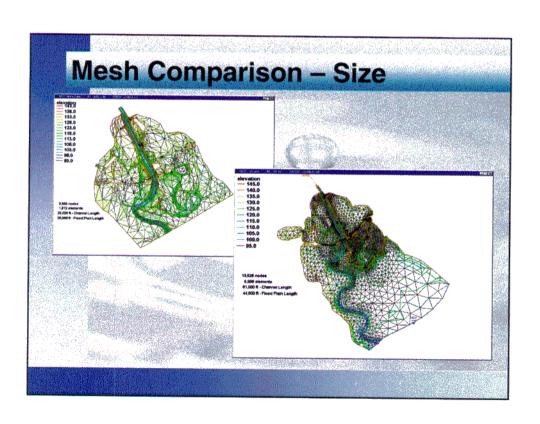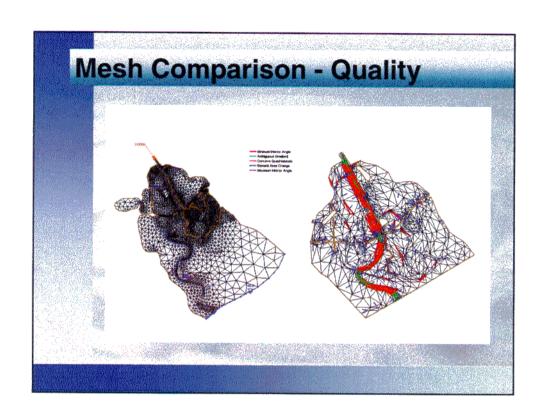

Mesh Generation Inside SMS

Visualization

- **Vector and Scalar Plots**
  - Elevations
  - Velocities/Velocity Magnitues
  - Water Surface Elevations
- **Animations and Flow Traces**
- **Mesh Quality Checks**
- **Solution Comparisons**

Mesh Comparison – Size
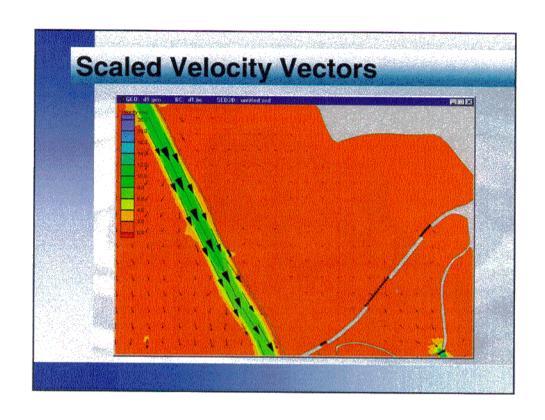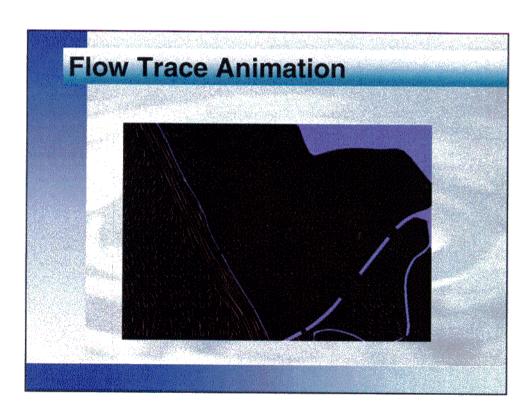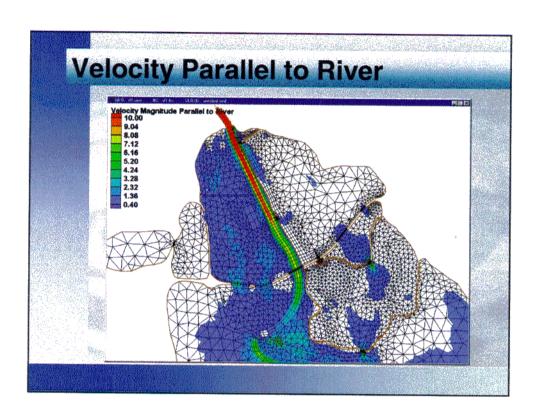
Mesh Comparison - Quality

Flow in Congaree River

Two-Dimensional flow behind Manning Levee

- **Visualization tools to illustrate**
  - Scaled Velocity Vectors (magnitude and direction)
  - Flow Tracing simulates die tracking
- **Effective Flow**
  - Compute magnitude in direction of river flow
  - Display contours for regions with flow greater than threshold value.

Scaled Velocity Vectors

Flow Trace Animation

Velocity Parallel to River

Conclusions

1. **Historical Factors**
   - Mannings' Levee greatly influences flow in Richland County Floodplain
   - Design and management of the Richland floodplain has been dominated by the existence and consideration of the Mannings' Levee.
   - I-77 relief openings not located for efficient floodway

2. **2-D flow behind Mannings' Levee**
   - Superior representation of Geometry
   - Superior distribution of elements
   - Superior element quality

Conclusions

3. **RMA2 Application Developed by Exponent Inc. is Superior to that Previously Used by FEMA**
   - Superior representation of Geometry
   - Superior distribution of elements
   - Superior element quality

4. **RMA2 Model Developed by Exponent Inc. Should be Used by FEMA to Determine the Floodway**

Questions?